Fluid Density and Impact Cavity Formation

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Abstract

Characteristics of the impact cavity formed when a steel ball is dropped into aqueous solutions of densities ranging from 0.98 g·cm^{-3} to 1.63 g·cm^{-3} were investigated. A high-speed camera was used to record the formation and collapse of the cavity. The results showed cavity diameter, volume, and pinch-off time are independent of fluid density, on average. There was an unexplained reduction in cavity formation for densities of 1.34 g·cm^{-3} and 1.45 g·cm^{-3}.

Keywords**:** impact cavity, fluid density, cavity diameter, cavity volume

I. INTRODUCTION

When a ball is dropped into a liquid, an impact cavity may be formed and evolve over a series of typical stages[1]. As shown in figure 1, a cylindrical cavity forms behind the ball as it moves into the liquid, (a). A slight constriction in the cylindrical cavity becomes visible as the ball moves deeper (b). The cavity begins to collapse, creating an air jet as the walls of the cavity move inward (c). The cavity pinches off, forming a 'crater' along with a trailing bubble of air (d). As the process continues, the cavity size reduces as the displaced water returns. Finally, as the cavity fully collapses, a back-jet of water is shot up into the air at high speed (e).

It has been shown that there is great variability in back-jet formation[2], and cavity diameter has been

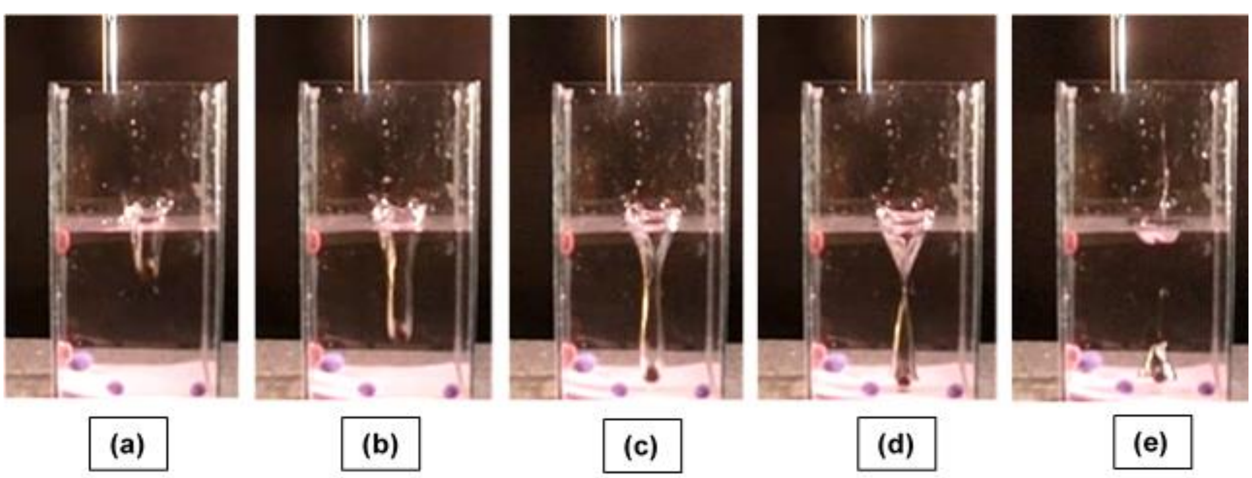

Figure 1. The process of cavity formation and collapse. Example from trial 1 of liquid density 0.98 g·cm^{-3}.

shown to be linearly dependent on impact velocity[3], but little has been published on the effect of fluid density on cavity formation. Here, we investigate the effect of fluid density on several characteristics of cavity formation: cavity volume, diameter, and time for cavity pinch-off.

Since the steel projectile used here has a much greater density than that of the liquid, the initial velocity of the displaced liquid is expected to be fairly constant across the range of densities tested. Increasing density of the liquid will increase both fluid pressure and mass proportionally, therefore the deceleration of the water after it is displaced, and then its acceleration as it collapses, is predicted to be independent of density.

During testing, it was observed that there was significant turbulence during the collapse of the cavity, thus pinch-off depth and cavity volume at pinch-off, although expected to be independent of density on average, will likely be quite variable.

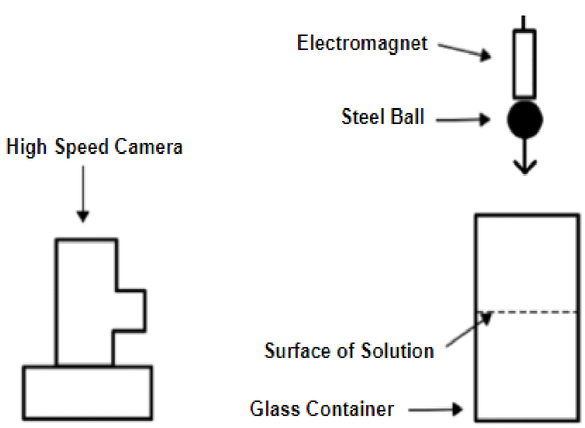

Figure 2. Diagram of the apparatus.

II. METHOD

An aqueous zinc chloride solution of volume 700 ml with density ranging from 0.98 g·cm^{-3} to 1.63 g·cm^{-3} was placed in a 20.2 cm high glass container, with solution depth of 12.6 cm. The steel ball, of diameter 1.20 cm, was released from a height of 0.50 m above the surface of the fluid without spin using an electromagnet. A high-speed, 1200 fps, camera was used to record the formation and collapse of the cavity. This was repeated five times for each of the six densities tested.

The videos were analyzed using Logger Pro. Cavity volume was found by plotting points of position along the side of the cavity at the time of pinch-off, as shown in Figure 3. The cavity volume (*V*) was determined by finding the integral of the plotted function displaying the position points, and then rotated 360˚ about the x-axis, using the formula

$$V = \int_{h_1}^{h_2} \pi f(x)^2 \, dx \qquad (1)$$

where h_1 is the position of the water surface, h_2 is the position of the bottom of the cavity at pinch-off, and $f(x)$ is the best-fit function.

Cavity diameter at pinch-off was found by using a known reference distance to accurately measure distance under the water. Finally, for time to pinch off, the number of frames between impact and pinch-off was counted, and then converted into seconds.

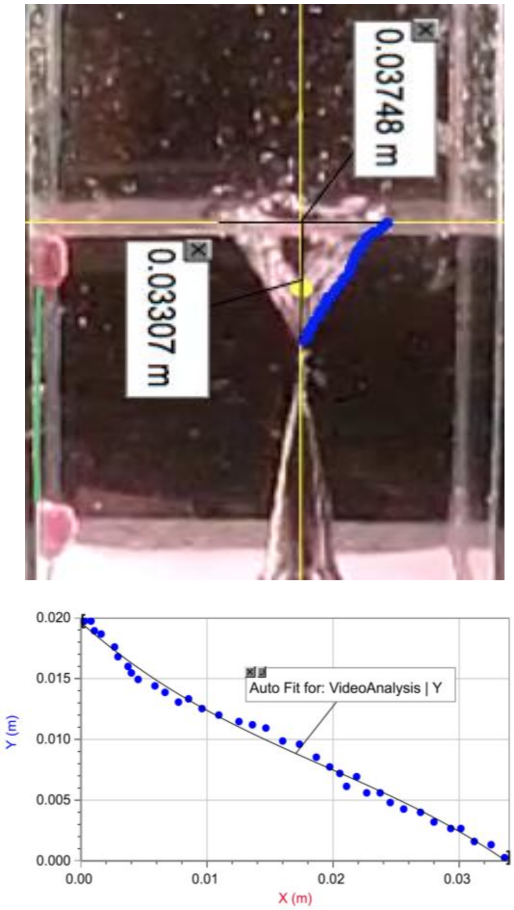

Figure 3. The wall of the cavity is plotted at pinch-off (blue dots). Axes are created, and cavity depth and width are measured. Then, the shape of the cavity is modelled with a function.

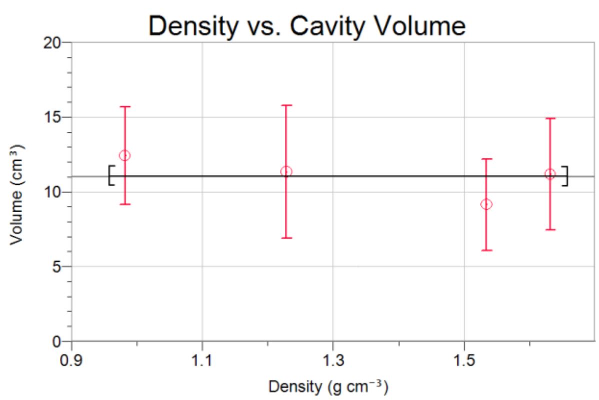

Figure 4. Cavity volume at pinch-off is, on average, independent of liquid density for the four densities shown here.

III. RESULTS AND DISCUSSION

As seen in Figure 4, cavity volume at solution densities 0.98, 1.23, 1.53 and 1.63 g·cm^{-3} is independent of density, within uncertainty. As predicted, the cavity volumes vary significantly, but on average fluid density has no effect on cavity volume at pinch-off for these four densities.

The diameter of the crater formed was also independent of density, as seen in figure 5. This was predicted, as both the fluid pressure and inertia are directly proportional to the density.

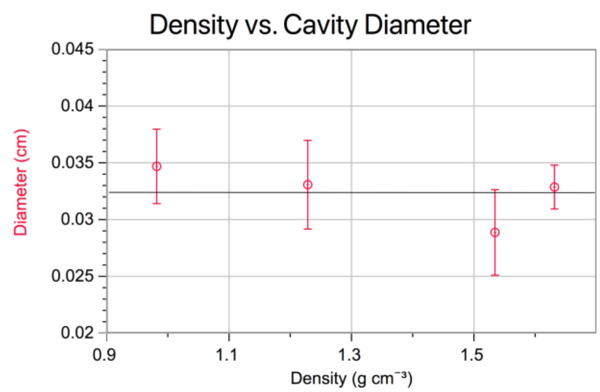

Figure 5. Cavity diameter at pinch-off is independent of density.

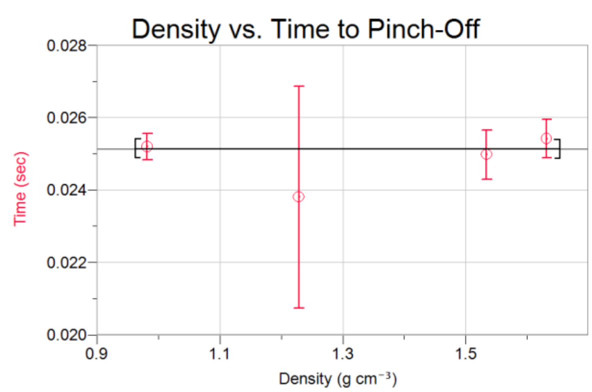

Figure 6. Time between impact and cavity pinch-off is shown here to be independent of density.

Finally, the time between impact and cavity pinch-off was consistent on average, occurring approximately 0.025 seconds after impact, as shown in figure 6. The reason for the much greater variability in cavity pinch-off time for the 1.23 g·cm^{-3} density is unknown.

For the densities of 1.34 and 1.45 g·cm^{-3}, the volume of the cavity was significantly less, as shown in figure 7. The reasons for this anomalous behavior is not fully understood, but one possible explanation is that cavity volume is dependent on factors such as surface tension and viscosity, which could not be controlled using the chosen method.

Figure 8 clearly shows the difference in the nature of the cavity formation between liquid densities of 1.63 and 1.45 g·cm^{-3}. The reasons for this difference are unknown. Further research is suggested into the factors that determine successful cavity formation on impact.

Considering other aspects of cavity formation and collapse, very little turbulence was seen during formation of the initial cylindrical cavity, but during pinch-off and collapse of the cavity, significant turbulence was observed near the walls of the cavity. This is likely the reason for the extreme variability seen in back-jet velocity[2], as well as the variability in cavity volume and diameter. The width of the initial cylindrical cavity, from top to bottom, was narrower by about 15% in the 1.63 g·cm^{-3} liquid compared to the 0.98 g·cm^{-3} liquid. Additionally, the cavity appeared to become slightly concave at pinch-off in the denser liquid. Further research is necessary to fully understand this behavior.

Further research on how ball velocity, size and surface affect the characteristics of cavity formation and collapse is needed. The effect of liquid surface tension and viscosity on cavity formation also need further study. Finally, an investigation into what occurred at densities of 1.34 and 1.45 g·cm^{-3} here to cause the lack of cavity formation is suggested.

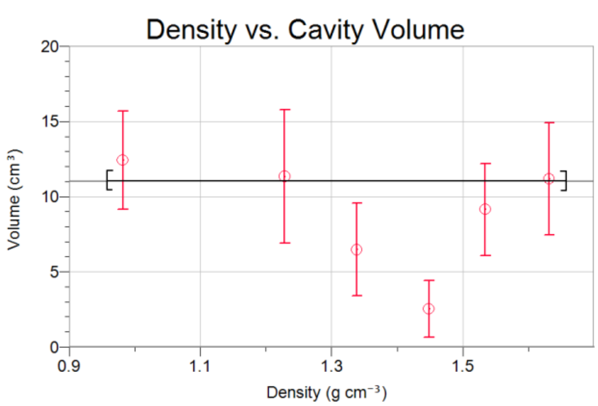

Figure 7. Cavity volume vs density for all six densities tested. The trailing air cylinder did not fully form for densities of 1.34 and 1.45 g·cm^{-3}

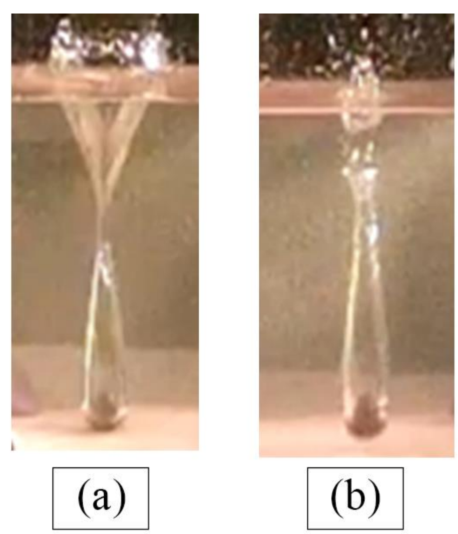

Figure 8. The cavity formation for liquid density 1.63 g·cm^{-3} (a) is clearly different from the cavity formation for 1.45 g·cm^{-3} (b).

IV. CONCLUSION

Cavity volume at pinch-off is shown to be, on average, independent of the density of zinc chloride solution, however there was high variability in the nature of the cavity formation. At two of the medium densities tested, cavity formation was much reduced for unknown reasons. For the densities at which cavity formation was consistent, cavity diameter and volume were on average independent of density as predicted, as was the time to cavity pinch-off.

V. REFERENCES

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